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Physics Reach of the LHCb Experiment

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Abstract. The physics prospects of the LHCb experiment are presented here for precision CP violation measurements and rare decays.

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1 Introduction

The LHCb experiment at CERN is a dedicated b-physics experiment and it is designed to perform precision measurements of CP symmetry violation. For this purpose, LHCb will constrain the triangles of Figure 1 representing the unitarity of the CKM matrix [1].

A large variety of final states involving b-hadrons will be produced in pp collisions at LHC energies. The LHCb experiment, thanks to a robust and efficient triggering and particle identification systems, will be able to exploit this large production, including also pure hadronic and multi-body final states. LHCb will be also capable of measuring CP violation effects with large statistics in new decay modes like $\mathrm{B_s^0} \to \mathrm{D_s^{\mp}K^{\pm}}$, $\mathrm{B_s^0} \to \mathrm{K^+K^-}$, $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$...

Thanks to the large $\mathrm{b\bar{b}}$ production yield, LHCb will also have the opportunity to investigate very rare decays of the b-mesons as for example $\mathrm{B^0} \to \mathrm{K^{*0}}\gamma$, $\mathrm{B^0} \to \mathrm{K^{*0}}\mu\mu$, $\mathrm{B_s^0} \to \mu\mu$, etc.

Besides, if New Physics is present, LHCb will have the sensitivity to spot possible new effects arising in the b-sector. As a matter of fact, new particles may arise in loop diagrams, modifying the SM predictions. This is very likely to happen in the b-sector, since almost any extension of the SM foresees additional sources of CP violation. For this reason, over-constraining the CKM unitarity triangle will be very important in order to disentangle the SM components from the New Physics ones.

2 Experimental Overview

The physics goals of the LHCb experiment are very challenging. In particular, the hot pp environment imposes a highly efficient trigger to reject the large amount of inelastic background ($\sigma_{\mathrm{b\bar{b}}}/\sigma_{\mathrm{inel.}} \approx 0.01$) as many particles in the detector

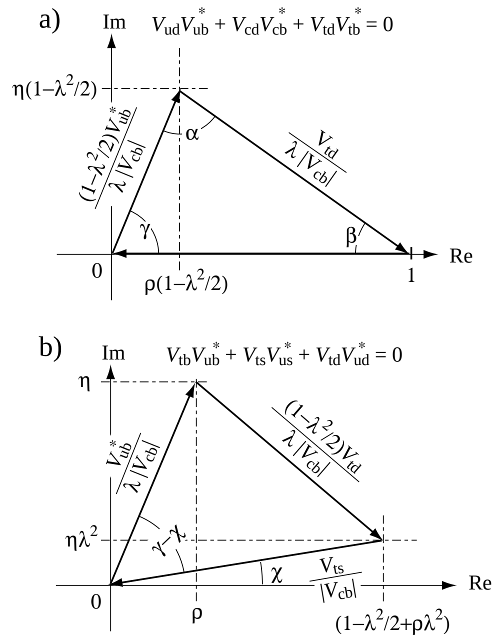

Fig. 1. *The two non-squashed unitarity triangles in the Wolfenstein's parametrisation [2].*

acceptance are not associated to b-hadron decays. The reconstruction of the decay of the B itself and the measurement of the asymetries is very demanding. One needs to have at the same time an effective π/K separation, an efficient trigger for non-leptons, and a good proper time resolution. On the other hand, LHCb can count on the large $\mathrm{b\bar{b}}$ yield of about 10^{12}/year of B^0, $\mathrm{B_s^0}$, $\mathrm{B_c}$ and other baryons with a good displacement from the primary interaction vertex ($\beta\gamma ct \approx 7$mm).

Figure 2 shows the non-bending plane of the LHCb spectrometer. Due to the large Lorentz boost, both the b and $\mathrm{\bar{b}}$ hadrons are mainly produced in the same forward direction.

The detector has recently undergone a reduction of material in front of RICH2 to reduce the interaction and radiation lenght in order to improve the tracking performance. Please refer to the following contributions for a detailed description of the LHCb detector and the design of the different subsystems [3–7].

3 Monte Carlo Simulation

The physics generator used is PYTHIA 6.2. The track multiplicity has been tuned to reproduce CDF+UA5 low energy data. This model includes the description of multiple parton-parton interaction with varying impact parameter. Multiple pp interactions in the same bunch crossing (pileup) are also included.

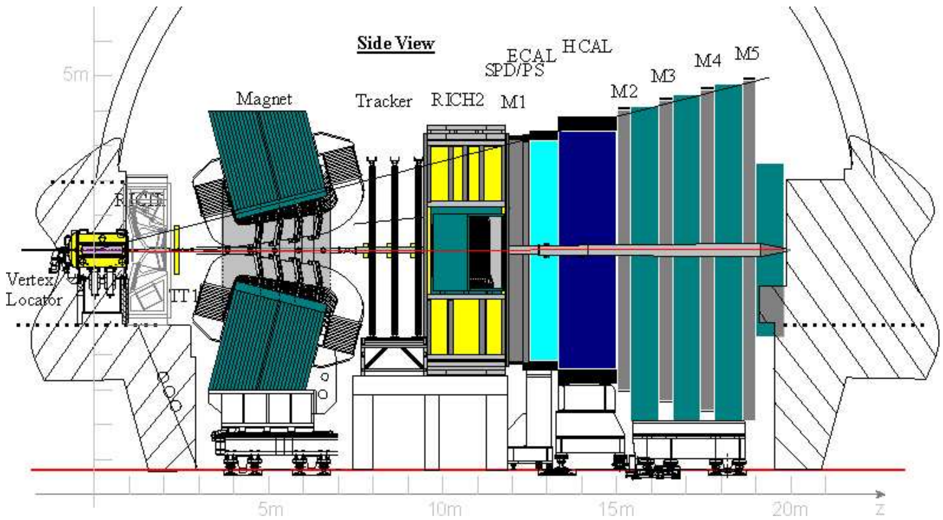

Fig. 2. *The LHCb detector in the non-bending plane section.*

The response of the detector is simulated in a realistic way including noise and 'spillover' effects (event acquisition can be affected by the previous or subsequent bunch crossing). Reconstruction and selection algorithms do not make use of the true Monte Carlo information at any stage. This means that track reconstruction, particle identification with RICH, calorimetry and muon systems are fully realistic.

About ten million $\mathrm{b\overline{b}}$ events in total have been simulated in this way and used to evaluate the event yields in many different decay channels.

4 Physics Performance

The simulated data have been used to quantify the physics performance of the detector. LHCb has proven to meet the performance requirements originally quoted in the Technical Proposal [8]. In particular, the realistic simulation reproduces good vertex resolutions, proper time and mass resolutions for almost all the studied decay channels. As an example, in the $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$channel, the z resolutions for the $\mathrm{D_s}$ and $\mathrm{B_s^0}$ decay vertices are $418 \pm 31\mu$m and $168 \pm 15\mu$m respectively. The proper time of $\mathrm{B_s^0}$ mesons reconstructed in this channel has a core resolution of 42 ± 5 fs, and it is dominated by the $\mathrm{B_s^0}$ vertex resolution. The $\mathrm{B_s^0}$ invariant mass resolution is 12.6 ± 0.6 MeV.

4.1 Event Yield

The untagged event rate Y is evaluated as,

$$Y = \int L(t)dt \times \sigma_{\mathrm{b\overline{b}}} \times 2 \times P(b \to b \text{ hadron}) \times \prod_i BR_i \times \varepsilon_{\mathrm{tot}}$$

integrating over the time of one year data taking at the nominal luminosity of 2×10^{32} cm^{-2}s^{-1}, which corresponds to a total of 2 fb^{-1} for $\sigma_{\mathrm{b\overline{b}}} = 500\mu$b. The efficiency $\varepsilon_{\mathrm{tot}}$, normalised to 4π, includes the geometrical acceptance, detection efficiency, Level-0 and Level-1 trigger efficiencies, reconstruction and selection cuts efficiencies. Table 1 summarises the expected yield for some of the studied physics channels.

Channel	$\varepsilon_{\mathrm{tot}}$	Yield
$\mathrm{B}^0 \to \pi^+\pi^-$	0.78%	27k
$\mathrm{B}^0 \to \mathrm{K}^+\pi^-$	0.85%	115k
$\mathrm{B_s^0} \to \mathrm{K}^+\mathrm{K}^-$	0.94%	35k
$\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$	0.26%	72k
$\mathrm{B_s^0} \to \mathrm{D_s^{\mp}K^{\pm}}$	0.34%	8k
$\mathrm{B_s^0} \to \mathrm{J}/\psi(\mu\mu)\phi$	1.66%	109k
$\mathrm{B_s^0} \to \mathrm{J}/\psi(\mathrm{ee})\phi$	0.29%	19k
$\mathrm{B}^0 \to \mathrm{J}/\psi(\mu\mu)\mathrm{K_S^0}$	0.76%	119k
$\mathrm{B}^0 \to \mathrm{K}^{*0}\gamma$	0.09%	20k

Table 1. *Total untagged event yields in various decay channels for one year of LHCb data taking.*

4.2 Flavour Tagging

The identification of the initial flavour of reconstructed B^0 and $\mathrm{B_s^0}$ mesons is necessary in order to study decays involving CP asymmetries and flavour oscillations. The statistical uncertainty on the measured CP asymmetries is directly related to the effective tagging efficiency $\varepsilon_{\mathrm{eff}}$, which is defined as

$$\varepsilon_{\mathrm{eff}} = \varepsilon_{\mathrm{tag}}(1 - 2\omega)^2\,, \tag{1}$$

where $\varepsilon_{\mathrm{tag}}$ is the tagging efficiency (probability that the tagging procedure gives an answer), and ω is the wrong tag fraction (probability for the answer to be incorrect when a tag is present).

Different algorithms have been developed to maximise the effective tagging efficiency and minimise the statistical error on the CP asymmetries. The opposite side lepton tag use the charge of the lepton from the semileptonic b decay and the charge of the kaon from the $\mathrm{b} \to \mathrm{c} \to \mathrm{s}$ decay chain. They also use the charge of the inclusive secondary vertex reconstructed from the decay products of the b-hadron.

Same side tagging determines directly the flavour of the signal B meson exploiting the correlation in the fragmentation chain. It is used to tag $\mathrm{B_s^0}$ mesons. If a $\mathrm{B_s^0}$ ($\mathrm{\overline{b}s}$) is produced in the fragmentation of a $\mathrm{\overline{b}}$ quark, an extra $\mathrm{\overline{s}}$ is available to form a K meson, which is a charged K, whose charge can tag the flavour, in about 50% of the times and a neutral K in the remaining cases.

Tagging Method	ε_{tag}	ω	ε_{eff}
muon tag	12.4	35.5	1.0 ± 0.1
electron tag	7.7	43.3	0.14 ± 0.07
kaon (opposite side)	26.3	36.2	2.1 ± 0.3
kaon (same side)	17.3	29.7	2.9 ± 0.3
vertex charge	23.9	40.0	0.9 ± 0.2
Total			**6.1±0.4**

Table 2. *Typical values in % for the tagging efficiency using* $\mathrm{B_s^0} \to \pi^+\mathrm{K}^-$, $\mathrm{K^+K^-}$, $\mathrm{D_s^-}\pi^+$ *triggered events.*

Table 2 shows typical values for the tagging efficiency in $\mathrm{B_s^0} \to \pi^+\mathrm{K}^-$, $\mathrm{K^+K^-}$, $\mathrm{D_s^-}\pi^+$ events after trigger requirements have been applied. The bottom line of the table represents the performance of the final tagging decision.

Same side tagging of $\mathrm{B^0}$ mesons using soft pions is under study and may be added in the future.

4.3 Sensitivity Studies

In this section we discuss the physics performance that can be obtained with the LHCb detector on the determination of the CKM angles of Figure 1. In the following, results from previous sensitivity studies, carried out at the time of the Technical Proposal [8], have been scaled based on the new event yields.

γ from $\mathrm{B^0} \to \pi^+\pi^-$ and $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ events

A strategy to determine the CKM angle γ has been proposed in [9] using a combination of measurements in $\mathrm{B^0} \to \pi^+\pi^-$ and $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ channels. This method relies on the exact U-spin symmetry, which is the only theoretical uncertainty. It allows for the simultaneous determination of ϕ_d and γ, provided that ϕ_s is known independently, for instance from $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ events. Besides, ϕ_d will also be known very precisely, and this can be used to further constrain the γ angle.

The sensitivity on the CP asymmetries $\mathcal{A}^{\text{dir}}$ and $\mathcal{A}^{\text{mix}}$ has been estimated with a toy Monte Carlo feeding it with the input values of Table 3. In one year of data taking, the sensitivity on the two asymmetries are expected to be:

$$\mathrm{B^0} \to \pi^+\pi^- : \quad \sigma(\mathcal{A}^{\text{dir}}) \approx \sigma(\mathcal{A}^{\text{mix}}) \approx 0.054 \qquad Corr(\mathcal{A}^{\text{dir}}, \mathcal{A}^{\text{mix}}) \approx -0.53$$

$$\mathrm{B_s^0} \to \mathrm{K^+K^-} : \quad \sigma(\mathcal{A}^{\text{dir}}) \approx \sigma(\mathcal{A}^{\text{mix}}) \approx 0.043 \qquad Corr(\mathcal{A}^{\text{dir}}, \mathcal{A}^{\text{mix}}) \approx 0.0$$

which corresponds to a sensitivity on the γ angle of the order of $\approx 3°$. In the $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ channel, CP asymmetries can still be measured up to $x_s = 40$ with an error increase of a factor 1.6.

Parameter	$B^0 \to \pi^+\pi^-$	$B_s^0 \to K^+K^-$
Yield	27k	35k
Bkg/Signal	0.8	0.55
x_d	0.755	20
$\mathcal{A}^{\mathrm{dir}}$	-0.30	0.16
$\mathcal{A}^{\mathrm{mix}}$	0.58	-0.17
$\Delta\Gamma$	0.0	0.0

Table 3. *Input values for the sensitivity study on* γ.

γ from $B_s^0 \to D_s^{\mp}K^{\pm}$ events

The decays $B_s^0 \to D_s^{\mp}K^{\pm}$, which are the strange counterpart of the $B^0 \to D^{*\pm}\pi^{\pm}$ mode, receive only contribution from tree diagrams. They can be used to measure $\gamma - 2\delta\gamma$ in a theoretically clean way [11]. Assuming that $\delta\gamma$ can be derived from $B_s^0 \to J/\psi\phi$ events, $B_s^0 \to D_s^{\mp}K^{\pm}$ events will provide a way to determine γ which is independent on possible new physics in B mixing.

Differently from $B^0 \to D^{*\pm}\pi^{\pm}$ decays, one of the diagrams in $B_s^0 \to D_s^{\mp}K^{\pm}$ decay is only suppressed by $R_b \approx 0.4$, so that intereference effects are much larger, yielding large asymmetries. On the other hand the selection of these events is challenging as the $B_s^0 \to D_s^-\pi^+$ background must be efficiently rejected, which can be attained with the help of the RICH systems.

In one year LHCb will reconstruct about 8k $B_s^0 \to D_s^{\mp}K^{\pm}$ events. Assuming for $\Delta m_s = 20\ \mathrm{ps}^{-1}$, the precision on γ will be of the order of $\approx 10°$, depending on the value of the strong phase difference and the value of $\Delta\Gamma_s/\Gamma_s$. Similar precision on γ should also be attainable with the $B^0 \to D^{*\pm}\pi^{\pm}$ mode, for which a new evaluation is under way.

β from $B^0 \to J/\psi K_S^0$ events

The $B^0 \to J/\psi K_S^0$ mode is the "gold-plated" channel explored at the B-factories at the $\Upsilon(4S)$ resonance. The CKM angle β is extracted from a fit to the time-dependent asymmetry,

$$\mathcal{A}^{\mathrm{CP}}(B^0 \to J/\psi K_S^0) = \mathcal{A}^{\mathrm{dir}} \cdot \sin \Delta m_d t + \mathcal{A}^{\mathrm{mix}} \cdot \sin \Delta m_d t = \sin 2\beta \cdot \sin \Delta m_d t\,,$$

where $\mathcal{A}^{\mathrm{dir}}$ is expected to be equal to 0 in the SM. LHCb data will bring a lot of statistics to this channel, and this will give the possibility to look into higher order effects and fit also $\mathcal{A}^{\mathrm{dir}}$. The experiment will collect in one year 120k events which will allow to measure sin2β with a statistical precision of ± 0.02, assuming $\beta = 20°$ as central value.

α from $B^0 \to \pi^+\pi^-$ events

Another benchmark CP mode is $B^0 \to \pi^+\pi^-$, which allows one to probe the CKM angle α. Unfortunately this mode is polluted by penguin diagrams contribution which may be non negligible. A reliable theoretical prediction of the 'penguin' to 'tree' ratio $|P/T|$, that could be as high as 0.2, is difficult. Nonetheless, if $|P/T|$ will be known to a level of precision of ± 0.1, the sensitivity on α would be in the range of $5° < \sigma_\alpha < 10°$ depending on the value of α in the range $50° < \alpha < 120°$ [10].

$\delta\gamma$ from $B_s^0 \to J/\psi\phi$ events

The decay $B_s^0 \to J/\psi\phi$ is particularly interesting as it gives access to the weak mixing phase $\phi_s = -2\delta\gamma = -2\lambda^2\eta$, and thus allowing to measure the Wolfenstein parameter η directly. Due to the small SM value of $\phi_s \approx 10^{-2}$, this channel offers a sensitive probe for CP-violating contributions beyond SM. Experimentally, the analysis is complicated by the fact that since both the ϕ and the J/ψ are vector meson, two orbital momentum states can occur, therefore an angular analysis of the decay final states is needed. This is feasible with the LHCb experiment thanks to the good proper time resolution of 36 ± 1 fs and the large statistical sample. The detector will collect in one year 109k $B_s^0 \to J/\psi(\mu\mu)\phi$ events and 19k $B_s^0 \to J/\psi(ee)\phi$ events. Assuming $\Delta m_s = 20$ ps^{-1}, the attainable precision on $2\delta\gamma$ is of the order of $2°$.

4.4 B_c mesons and rare decays

The observation of the B_c meson by the CDF collaboration in the channel $B_c \to J/\psi l\nu$, with measured mass and lifetime [12]

$$M_{B_c} = 6.4 \pm 0.4 \pm 0.1 \text{ GeV}, \quad \tau = 0.46 \pm 0.17 \pm 0.03 \,\text{ps},$$

opens up the experimental investigation on the $\overline{b}c$ hadronic system. Aside from the interest that the B_c meson rises in QCD, these type of events can provide information on CP in decay channels like $B_c \to J/\psi\pi$, $B_c \to D_sD$, $B_c \to J/\psi D$, etc. LHCb will be able to collect 12k $B_c \to J/\psi\pi$ events in one year data taking with a mass resolution of 19 MeV.

Another interesting field is the observation of rare decays of the B. In the SM, flavour-changing neutral current decays involving $b \to s$ or $b \to d$ transitions only occur at loop-level, and come with very small BR $\approx O(10^{-5})$ providing a sensitive probe for new physics. Amongst the other channels, the LHCb detector will yield about 20k $B^0 \to K^{*0}\gamma$ events per year, with a mass resolution of 72 MeV and a high purity statistical sample.

Parameter	Channel	Precision
γ	$B_s^0 \to D_s^{\mp}K^{\pm}$	$\sigma_\gamma \approx 10^\circ$
	$B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$	$\sigma_\gamma \approx 3^\circ$
β	$B^0 \to J/\psi K_S^0$	$\sigma_\beta \approx 0.6^\circ$
α	$B^0 \to \pi^+\pi^-$	$\sigma_\alpha \approx 5^\circ - 10^\circ$
$2\delta\gamma$	$B_s^0 \to J/\psi\phi$	$\sigma_{2\delta\gamma} \approx 2^\circ$
$\|V_{td}/V_{ts}\|$	$B_s^0 \to D_s^-\pi^+$	Δm_s up to 58 ps^{-1}

Table 4. *Physics sensitivities on CKM parameters after one year LHCb data taking, corresponding to an integrated luminosity of 2 fb^{-1}.*

5 Summary and Conclusion

Table 4 summarises the main results on the sensitivity studies on the CKM mixing matrix parameters. Results in this table are preliminar and they will be superseded in the forthcoming reoptimization Technical Design Report.

The LHCb experiment demontrates to be able to perform precision measurements in order to over-constrain the unitarity triangle, giving the opportunity to look also for new physics.

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